AFRL-RX-WP-JA-2016-0305

MODEL-BASED INVERSE METHODS FOR SIZING CRACKS OF VARYING SHAPE AND LOCATION IN BOLT-HOLE EDDY CURRENT (BHEC) INSPECTIONS (POSTPRINT)

Eric A. Lindgren and Ryan Mooers
AFRL/RX

John C. Aldrin
Computational Tools

Harold A. Sabbagh, Liming Zhao, Elias Sabbagh, and R. Kim Murphy
Victor Technologies

Mark Keiser, Jennifer Flores-Lamb, David S. Forsyth, and Doyle Motes
TRI/Austin

7 October 2015
Interim Report

Distribution Statement A.
Approved for public release: distribution unlimited.

© 2016 AIP PUBLISHING LLC

(STINFO COPY)

AIR FORCE RESEARCH LABORATORY
MATERIALS AND MANUFACTURING DIRECTORATE
WRIGHT-PATTERSON AIR FORCE BASE, OH 45433-7750
AIR FORCE MATERIEL COMMAND
UNITED STATES AIR FORCE

REPORT DOCUMENTATION PAGE	*Form Approved* *OMB No. 0704-0188*

The public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Department of Defense, Washington Headquarters Services, Directorate for Information Operations and Reports (0704-0188), 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to any penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number. **PLEASE DO NOT RETURN YOUR FORM TO THE ABOVE ADDRESS**.

1. REPORT DATE ***(DD-MM-YY)***	**2. REPORT TYPE**	**3. DATES COVERED** ***(From - To)***
7 October 2015	Interim	6 May 2010 – 7 September 2015

4. TITLE AND SUBTITLE

MODEL-BASED INVERSE METHODS FOR SIZING CRACKS OF VARYING SHAPE AND LOCATION IN BOLT-HOLE EDDY CURRENT (BHEC) INSPECTIONS (POSTPRINT)

5a. CONTRACT NUMBER
FA8650-10-D-5210

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)

1) Eric A. Lindgren and Ryan Mooers – AFRL/RX

2) John C. Aldrin – Computational Tools

(continued on page 2)

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER
X0N6

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

1) AFRL/RX
Wright-Patterson AFB, OH 45433

2) Computational Tools
4275 Chatham Avenue
Gurnee, IL 60031

(continued on page 2)

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

Air Force Research Laboratory
Materials and Manufacturing Directorate
Wright-Patterson Air Force Base, OH 45433-7750
Air Force Materiel Command
United States Air Force

10. SPONSORING/MONITORING AGENCY ACRONYM(S)
AFRL/RXCA

11. SPONSORING/MONITORING AGENCY REPORT NUMBER(S)
AFRL-RX-WP-JA-2016-0305

12. DISTRIBUTION/AVAILABILITY STATEMENT
Distribution Statement A. Approved for public release: distribution unlimited.

13. SUPPLEMENTARY NOTES
PA Case Number: 88ABW-2015-4810; Clearance Date: 7 Oct 2015. This document contains color. Journal article published in AIP Conference Proceedings, Vol. 1706, No. 1, 10 Feb 2016. © 2016 AIP Publishing LLC. The U.S. Government is joint author of the work and has the right to use, modify, reproduce, release, perform, display, or disclose the work.
The final publication is available at http://dx.doi.org/10.1063/1.4940557

14. ABSTRACT ***(Maximum 200 words)***
A comprehensive approach is presented to perform model-based inversion of crack characteristics using bolt hole eddy current (BHEC) techniques. Data was acquired for a wide range of crack sizes and shapes, including mid-bore, corner and through-thickness crack types, and from both standard eddy current hardware and a prototype BHEC system with z-axis position encoding. Signal processing algorithms were developed to process and extract features from the 2D data sets, and inversion algorithms using VIC-3D generated surrogate models were used for inverting crack size. New model results are presented, which now address the effect of having a corner crack at an edge and a through crack adjacent to two edges. A two-step inversion process was implemented that first evaluates the material layer thickness, crack type and location, in order to select the most appropriate VIC-3D surrogate model for subsequent crack sizing inversion step. Inversion results for select mid-bore, through and corner crack specimens are presented where sizing performance was found to be satisfactory in general, but also depend on the size and location of the flaw.

15. SUBJECT TERMS
Bolt hole eddy current (BHEC); mid-bore, corner and through-thickness crack types; VIC-3D generated surrogate models

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT:**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON** (Monitor)
a. REPORT	**b. ABSTRACT**	**c. THIS PAGE**			Eric Lindgren
Unclassified	Unclassified	Unclassified	SAR	14	**19b. TELEPHONE NUMBER** *(Include Area Code)* (937) 255-9800

REPORT DOCUMENTATION PAGE Cont'd

6. AUTHOR(S)

3) Harold A. Sabbagh, Liming Zhao, Elias Sabbagh, and R. Kim Murphy - Victor Technologies

4) Mark Keiser, Jennifer Flores-Lamb, David S. Forsyth, and Doyle Motes - TRI/Austin

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

3) Victor Technologies LLC, 2609 S Spicewood Ln,
Bloomington, IN 47401

4) TRI/Austin, 9063 Fm 2244 Rd, Austin, TX 78746

Model-based Inverse Methods for Sizing Cracks of Varying Shape and Location in Bolt-hole Eddy Current (BHEC) Inspections

John C. Aldrin[2, a)], Harold A. Sabbagh[3, b)], Liming Zhao[3, c)], Elias Sabbagh[3, d)], R. Kim Murphy[3, e)], Mark Keiser[4, f)], Jennifer Flores-Lamb[4, g)], David S. Forsyth[4, h)], Doyle Motes[4, i)], Eric A. Lindgren[1, j)], and Ryan Mooers[1, k)]

[1]*Air Force Research Laboratory (AFRL/RXCA), Wright-Patterson AFB, OH 45433*
[2]*Computational Tools, 4275 Chatham Avenue, Gurnee, IL 60031*
[3] *Victor Technologies LLC, Bloomington, IN 47401*
[4] *TRI/Austin, Austin, TX 78746*

a) aldrin@computationaltools.com
b) has@sabbagh.com
c) zhou@sabbagh.com
d) ehs@sabbagh.com
e) rkmurphy@att.net
f) mkeiser@tri-austin.com
g) jfloreslamb@tri-austin.com
h) dforsyth@tri-austin.com
i) dmotes@tri-austin.com
j) eric.lindgren@us.af.mil
k) ryan.mooers.1@us.af.mil

Abstract. A comprehensive approach is presented to perform model-based inversion of crack characteristics using bolt hole eddy current (BHEC) techniques. Data was acquired for a wide range of crack sizes and shapes, including mid-bore, corner and through-thickness crack types, and from both standard eddy current hardware and a prototype BHEC system with z-axis position encoding. Signal processing algorithms were developed to process and extract features from the 2D data sets, and inversion algorithms using VIC-3D generated surrogate models were used for inverting crack size. New model results are presented, which now address the effect of having a corner crack at an edge and a through crack adjacent to two edges. A two-step inversion process was implemented that first evaluates the material layer thickness, crack type and location, in order to select the most appropriate VIC-3D surrogate model for subsequent crack sizing inversion step. Inversion results for select mid-bore, through and corner crack specimens are presented where sizing performance was found to be satisfactory in general, but also depend on the size and location of the flaw.

INTRODUCTION

The use of eddy-current methods to detect damage in aircraft is well established, and is a key item to ensure that the risk of structural failures meets the requirements of the Aircraft Structural Integrity Program (ASIP) of the United States Air Force. As maintenance of structural components of aircraft moves from time-based maintenance to condition-based maintenance, there is a need for innovative methods to not simply detect damage, but to completely characterize the damage state [1]. Fatigue crack characterization using eddy current methods is one of the most significant opportunities for condition-based maintenance. To address this need, recent research into model-based

42nd Annual Review of Progress in Quantitative Nondestructive Evaluation
AIP Conf. Proc. 1706, 090020-1–090020-11; doi: 10.1063/1.4940557
© 2016 AIP Publishing LLC 978-0-7354-1353-5/$30.00

Distribution A. Approved for public release (PA): distribution unlimited.

inverse inversion methods for the characterization of surface-breaking cracks using in-service eddy current hardware has been investigated [2-6]. However, the problem of sizing cracks in bolt holes of aircraft structures is especially challenging when one considers the various materials used (for example: aluminum, titanium, and steel), the complex structural environments including compound curvatures and/or multiple layers that are fastened together, and the potential locations for cracks in the multi-layer joint.

Building on this recent work [3], a model-based inversion approach is presented for sizing cracks in fastener sites using existing bolt hole eddy current (BHEC) techniques. This process includes fast forward models, the use of feature extraction to minimize the complexity of the inversion problem, a model calibration and verification process, a multi-stage inverse method parameter estimation technique, and a software environment to facilitate inversion applications. The goal in this paper is to demonstrate crack sizing with variability in location, for example, at the edges of bolt holes, and address a wide array of potential crack shapes (e.g. mid-bore, through, and corner). Data was acquired from both a standard eddy current hardware setup and a prototype BHEC system with z-axis position encoding for a large set of crack specimens. The test specimens covered a wide range of crack sizes and shapes, including mid-bore, through-thickness, and corner crack types as shown in Figures 1(a), 1(b) and 1(c) respectively. New model results are also presented, which now address the effect of having a corner crack at an edge and a through crack adjacent to two edges. A two-step inversion process is presented that first evaluates the material layer thickness, crack type and location in order to select the most appropriate VIC-3D surrogate model for crack sizing. The final step in the inversion process simultaneously evaluates crack depth, length, and width (opening) for the eddy current signal. Inversion results for select crack data are presented along with trends in the experimental response for varying crack location and size. Lastly, progress will be presented on the development of a model-based inversion user interface to support NDE engineers and inspectors with the model calibration and model-based inversion tasks.

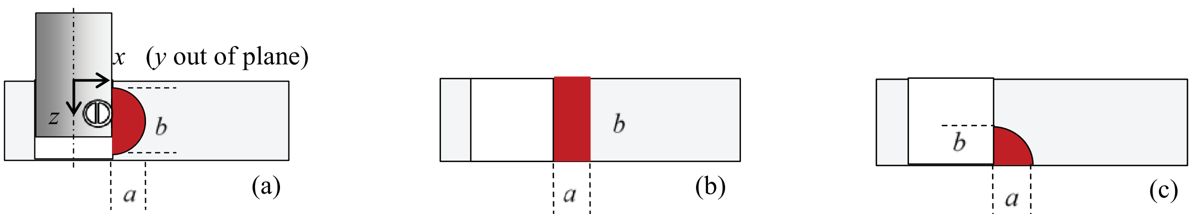


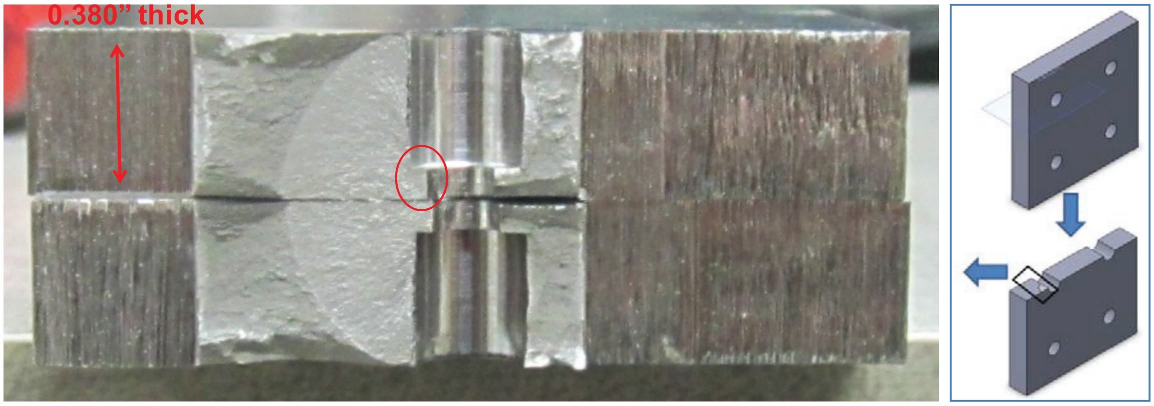
FIGURE 1. BHEC inversion problems with varying crack shape: (a) mid-bore, (b) through and (c) corner crack characterization

BHEC EXPERIMENTAL STUDIES

A case study problem for this proof-of-concept model-based inversion demonstration addresses flaw characterization for a BHEC technique using a rotating eddy current probe to inspect fastener sites for fatigue cracks. BHEC techniques are widely used for aerospace structure component inspection. Because the eddy current response will vary as a function of crack size, location, and profile, this problem provides a good opportunity to realize crack characterization through automated data analysis and model-based inversion. The key parameters that are to be estimated are the critical flaw dimension, depth, a, in Figure 1, as well as the crack length, b, crack width, w, and crack location with respect to the top of the hole, z_0, shown in Fig. 1(a).

In prior work [3], experimental results were only acquired from a limited set of mid-bore and through cracks. No well-characterized corner crack specimens were available at that time. In this study, corner cracks were manufactured in aluminum specimens by TRI/Austin. Starter notches were used, as shown in Figure 2(b), to initiate the cracks from the end of the holes prior to being machined away. The test specimen design was based on a prior multi-layer crack validation MR MAUS POD specimen design [6], as shown in Fig. 2(b). By using this same configuration, great flexibility is now available for producing a variety of multi-layer stack-ups with varying plate thickness and crack combinations. Corner cracks were grown in 7075-T6 Al specimens with three different thicknesses, 0.250”, 0.375”, and 0.500”. Crack dimensions for only the 0.250" specimens are presented in Table 1 using measurements for surface length and calculations for the bore length, bore depth, and surface depth of the cracks. All holes are 0.250" in diameter. The relationship between the bore and surface depth and the actual (internal) bore surface length and exterior surface length is based on quantitative relations determined from fractographic examinations of destructively characterized (break-open) specimens cycled using marker band loading spectra.

Distribution A. Approved for public release (PA): distribution unlimited.



(a) (b)

FIGURE 2. (a) Faces of a specimen with a corner crack initiating from a starter notch and (b) view of a 4 hole specimen with corner crack at hole

TABLE 1. Manufactured corner crack specimens

Specimen #	Material	Thickness (in)	Crack Orientation	Surface Length (in)	Surface Penetration Length (in)	Bore Length (in)	Bore Penetration Length (in)	Aspect Ratio
283	7075-T6 Al	**0.500**	External	**0.0517**	0.0548	0.0899	0.0934	1.70
317	7075-T6 Al	**0.500**	Internal	**0.1054**	0.1103	0.1857	0.1916	1.74
330	7075-T6 Al	**0.500**	Internal	**0.1530**	0.1595	0.2606	0.2676	1.68

In this study, data were acquired using two eddy current systems: the standard USAF eddy current hardware and a prototype automated BHEC (ABHEC) system with z-axis position encoding. The first setup used an Olympus Nortec 500D eddy-current unit with a Nortec Mini-Mite bolt hole scanner and a VM Split-D probe. The calibration and testing procedure followed generally accepted procedures for aerospace applications. The Mini-Mite scanner was mounted to a height gauge to record the location of each reading in depth (z). Experimental data from the probe was acquired and extracted in the circumferential direction around the hole and different depths at 10 mil increments into the hole, totaling over 10,000 eddy current measurements. Probe test frequencies of 200 and 500 kHz were used; however, results are only presented for 200 kHz in the paper. Special signal processing algorithms were developed to extract and process the 2D data necessary for model-based inversion.

The second system, a prototype UniWest EVI (ABHEC) system, was used with a limited sample set. Data acquisition and post processing for the ABHEC system was much more straightforward. A software routine was provided by UniWest that converts the original binary UniWest data into a structured .csv file which can be easily read into any post-processing software. This file includes all meta-data on the scans, two channels of differential probe data and two channels of absolute coil data for each frequency tested, as well as z-axis and rotational (circumferential) positioning for all the eddy current measurements. Some simple post-processing was also implemented to re-organize the data file into a 2D data matrix for indication sizing. Results from the UniWest ABHEC system for a corner crack specimen (#283) in a 0.500" aluminum plate are presented in Figure 3. One great advantage of the ABHEC system is that absolute measurement data is acquired, providing clear indications of where the layers start and end. For inverting the eddy current data, the 2D data grid shown in Figure 3 (top – left, middle) was reduced to two characteristic vectors (bottom) for each channel of data. First, the maximum response in the hole bore (z) direction is evaluated, providing a correlated response with the crack length and crack profile (shape). Second, a characteristic eddy current response in the hole circumferential (x') direction is extracted through the crack/notch peak response in z. Both vertical (V_y) and horizontal (V_x) components of the eddy current response are recorded, resulting in four data vectors being used for inversion.

Distribution A. Approved for public release (PA): distribution unlimited.

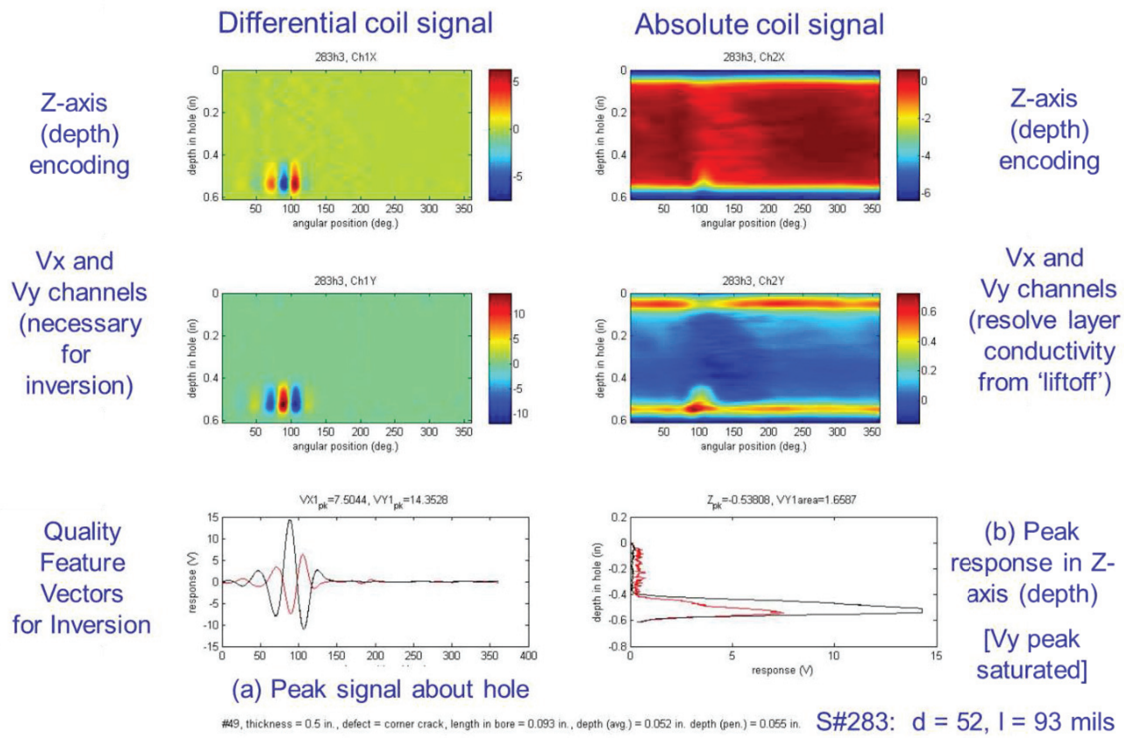


FIGURE 3. Raw data from the UniWest ABHEC system for a 0.052" x 0.093" corner crack in a 0.500" aluminum layer

BHEC MODEL DEVELOPMENT AND INVERSION APPROACH

In prior work, a comprehensive approach was presented for model-based inversion design to ensure the reliability of the inverse methods [3]. In this study, the goal is to extend the process to better address cracks located at edges and address varying shapes. The model for the BHEC split-D differential probe was again implemented in VIC-3D®. A model of the complete split-D differential probe with ferrite cores was created using a 32×32×8 grid mesh. The ferrite D cores were assigned a relative permeability of 2000. The cracks were modeled as either rectangular blocks (for through cracks) or semi-ellipses (for mid-bore or corner cracks) within a slab with a conductivity of $\sigma = 1.8966 \times 10^7$ S/m (32.7% IACS), corresponding to 7075-T6 Al. Because the flaws that were modeled are large compared to the skin depth, the requisite grids must contain enough cells to accurately model both the 'geometric and electrical scenes.' That is, there must be enough elements to both capture, in depth, the semi-elliptical shape of the flaws, as well as the variations of the incident field.

The current version of VIC-3D® cannot yet model a probe within the bolt hole. Note, that theoretical and numerical methods have been developed, and are currently being transitioned into VIC-3D® [7]. However, some outstanding challenges concerning computational times exist. To overcome this limitation, an approximation was made using a locally flat aluminum layer at the crack in the hole (see Figure 4). Additionally, large void regions were added to the model to address adjacent edges. For corner cracks, a single void region is added adjacent to the corner crack, as shown in Figure 4(a). Figures 4(b) and 4(c) show how two edges can be approximated by two large void regions. Note, for this model, the volume element flaw region mesh included the combined notch and two air blocks within a single VIC-3D® layer.

To model real cracks, it is desirable to be able to simulate crack opening widths down to 0.125 mils. However, to simulate very thin flaws using the volume element method, one must significantly increase the discretization of the notch in the lateral (notch length) direction to converge numerically to the correct solution. Convergence studies in VIC-3D® have been previously presented [3] to evaluate how well the numerical method converges for more narrow flaws for varying width and increasing notch discretization. In practice, such high levels of discretization do converge, but can take significant time to solve. To practically simulate thin cracks, an extrapolation scheme is used. In prior

Distribution A. Approved for public release (PA): distribution unlimited.

work, very good agreement of less than 1% error was demonstrated between the extrapolation model-based results and simulated VIC-3D® results for a 0.125 mil notch width with very high levels of discretization up to 2x512x32 [3]. When edges are present, simulated notch widths were limited to 6 mils and 3 mils because of the need to mesh the large edge region in the scan direction (width of the flaw direction). A mesh of 32x32x8 was used for the flaw region for 6 mil notches and 64x32x8 was used for the flaw region for 3 mil notches, in order to maintain the same volume element sizes in length and depth. Extrapolation was used to evaluate the response for cracks using solved results for 6 mils and 3 mils (this approach is supported by convergence studies presented in ref. [3]).

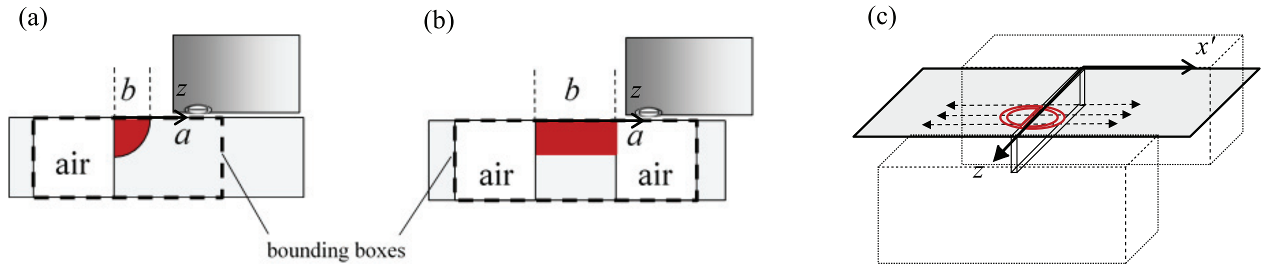


FIGURE 4. Approximate VIC-3D® models for unwrapped bolt-hole and crack. Views in 2D shown for (a) a corner crack with one adjacent edge and (b) a through crack with two edges, (c) 3D view of a through with two edges

Next, surrogate models were created from the results of the numerical simulations to greatly improve the speed and performance of the inverse methods. Frequently, data structures or look-up tables are constructed and interpolation schemes are applied to provide a fast means of sampling the call model over a wide range of conditions. Six surrogate models were created for the following corner, through and mid-bore crack cases:

1. Mid-bore cracks for either elliptical or rectangular notch profiles: depth = [100 75 50 25 12.5 0] mils, length = [250 200 150 100 50 25 0] mils, and width = [6 3 1 0.125] mils
2. Through thickness cracks (with 2 edges) in 0.125" thick panels: depth = [100 87.5 75 67.5 50 37.5 25 12.5 0] mils, and width = [6 3 0.125] mils,
3. Through thickness cracks (with 2 edges) in 0.250" thick panels (with same table dimensions),
4. Through thickness cracks (with 2 edges) in 0.375" thick panels (with same table dimensions),
5. Through thickness cracks (with 2 edges) in 0.500" thick panels (with same table dimensions),
6. Isolated corner cracks (adjacent to 1 edge): depth = [100 75 50 25 0] mils, length = [200 150 100 50 0] mils, and width = [6 3 0.125] mils.

All simulations were 2D raster scans (15 or more steps in z and 57 steps in x'). Even after making the above compromises, the total time for all these simulations was roughly 2 weeks. All the approximate surrogate model data were organized and provided as function calls for the Matlab inversion code. A cubic spline function was used to interpolate between simulated flaw size results, and a linear fit was used to extrapolate the response down to the 0.125 mil notch.

Figure 5 shows the simulated reactance (X) for the BHEC scans of corner cracks into the bolt hole (in z) with varying lengths (from 200 mils to 50 mil, up to down) and varying depths (100 mils to 25 mils, left to right). Figure 6 shows the simulated resistance (R) for the BHEC scans of corner cracks in the circumferential direction with varying lengths (from 100 mils to 50 mil, up to down) and varying depths (100 mils to 25 mils, left to right). In both figures, the simulated results were solved for notch widths of 6 mils (black) and 3 mils (red). The extrapolation approach for thin flaws appears to be reasonable. The notch opening has very little effect on the resistance, but a significant effect on the reactance.

Figure 7 presents an example of the simulated resistance (R) for the BHEC scans of through cracks in depth (z) with varying depths (12.5 mils and 25 mils, left to right) and varying lengths / plate thicknesses (0.125", 0.25", 0.375", and 0.50"). Simulated results were solved for notch widths of 6 mils (black) and 3 mils (red). It is interesting that the narrowest panel thickness has the largest resistance amplitude. To size these cracks, both amplitude and profile trends (in the bore) are needed to differentiate the different sizes. Note that based on these data trends simulated at 200 kHz, there is an observed lack of sensitivity (change) in the eddy current response for flaws greater than 50 mils deep (a) due to limited skin depth at this frequency.

Distribution A. Approved for public release (PA): distribution unlimited.

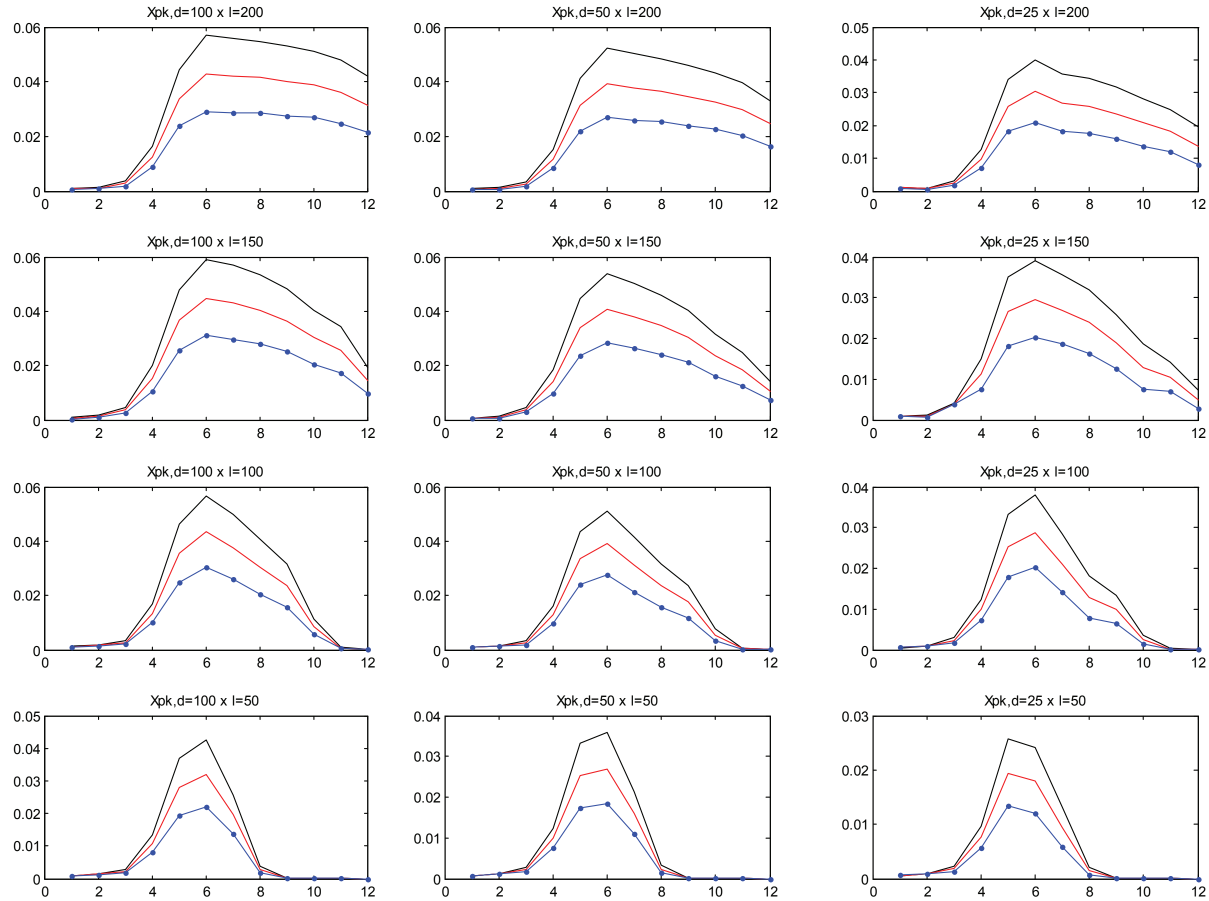


FIGURE 5. Simulated reactance (X) for the BHEC scans of corner cracks in the depth (z) dimension with varying lengths (from 200 mils to 50 mil, up to down) and depths (100 to 25 mils, left to right). Simulated results were solved for notch widths of 6 mils (black) and 3 mils (red). Extrapolation was used to produce simulated responses for a real crack width (~0.125 mils, blue dots)

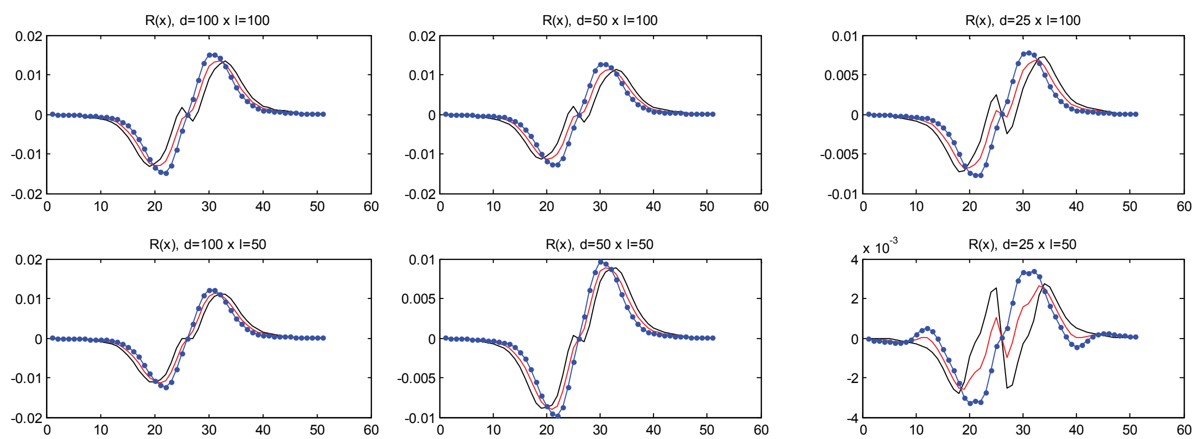


FIGURE 6. Simulated resistance (R) for the BHEC scans of corner cracks in the circumferential direction with varying lengths (from 100 mils to 50 mil, up to down) and depths (100 to 25 mils, left to right). Simulated results were solved for notch widths of 6 mils (black) and 3 mils (red). Extrapolation was used to produce simulated responses for a real crack width (~0.125 mils, blue dots)

Distribution A. Approved for public release (PA): distribution unlimited.

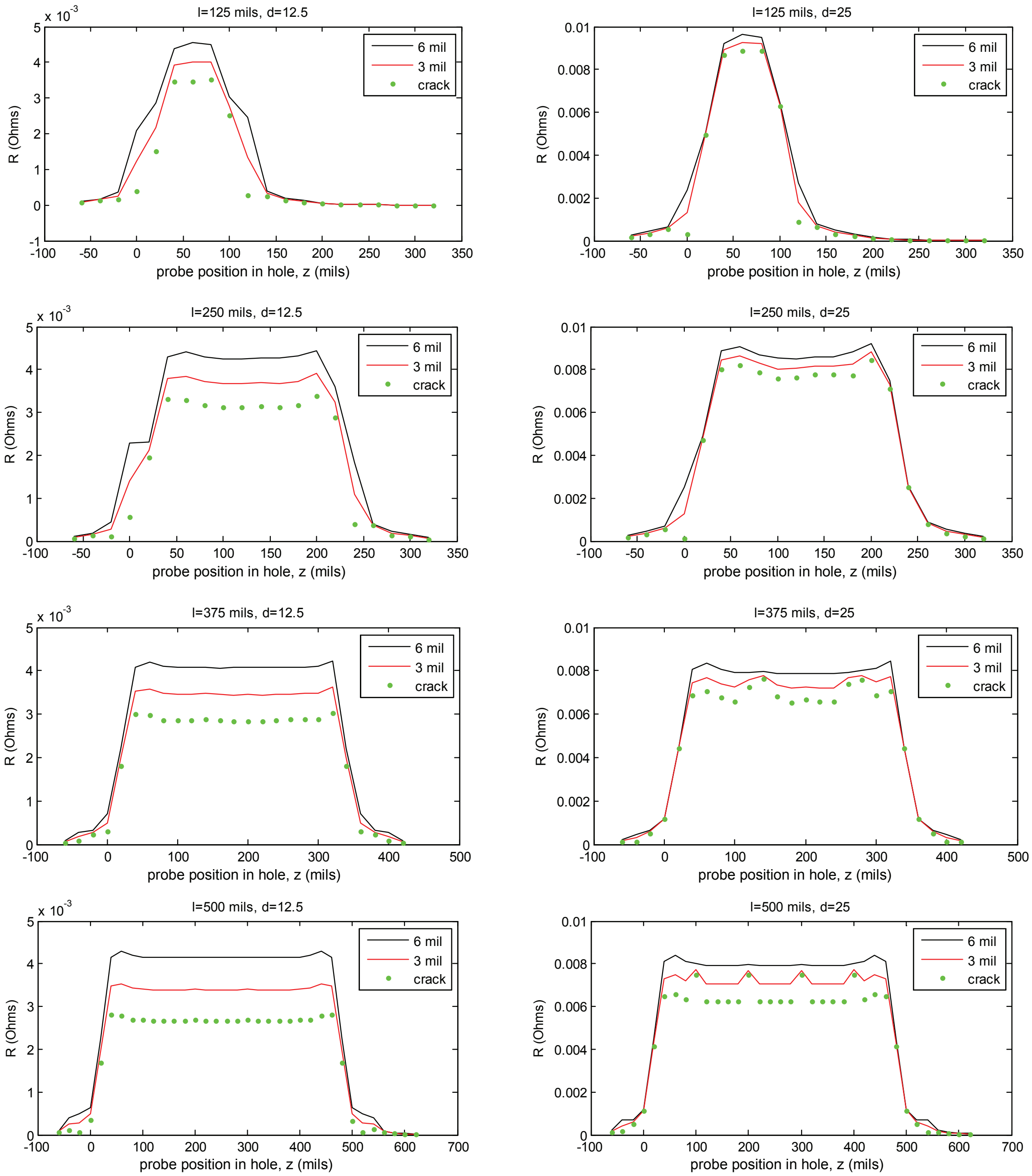


FIGURE 7. Simulated resistance (R) for the BHEC scans of through cracks in the depth (z) dimension with varying depths (12.5 mils and 25 mils, left to right) and lengths / plate thicknesses (0.125", 0.25", 0.375", and 0.50") Simulated results were solved for notch widths of 6 mils (black) and 3 mils (red). Extrapolation was used to produce simulated responses for a real crack width (~0.125 mils, green dots)

Eddy current simulations are designed to represent the change in impedance of an eddy current probe interacting with a test specimen. However, conventional eddy current measurement systems typically operate with the probe balanced over the test specimen and output voltage data. Thus, a model calibration step is a necessary in practice to equate the measurement data with simulated results that mimic the NDE technique procedure. The simulated and experimental 'calibration' results for a known flaw were used to develop a *beta-scale* factor to transform the BHEC system voltage output into the impedances that VIC-3D® requires. This relationship is given as follows:

Distribution A. Approved for public release (PA): distribution unlimited.

$$V_m(x',z) = \alpha + \beta \times \Delta Z_j(x',z); \quad m = X, Y, j = R, X . \tag{1}$$

With the calibrated surrogate model, the inversion step can be performed using the processed experimental BHEC data. A two-step inversion process was developed that first evaluates the material layer thickness, crack type, and location, in order to select the most appropriate VIC-3D surrogate model for crack sizing. The final step in the inversion process is simultaneously evaluating crack depth, length, and width (opening) for the eddy current signal. A nonlinear least-squares estimator (NLSE) is used to perform the inversion process. An iterative scheme is implemented that varies the initial conditions of the inverse problem and selects the most-repeatable results that minimize the difference between the experimental results and the estimated model to avoid local minima.

RESULTS

Inversion results are first presented for three well-characterized through cracks. While a great deal of through crack specimens were available from prior work, few of the cracks are shallow in depth, below 50 mils deep. Therefore, the focus of these verification studies is on select smaller cracks from this set. Using the new inversion process, the first step was to select the appropriate surrogate model for the detected layer thickness of 0.100". Next, based on the EC profile (in depth), the surrogate model for a through crack in a thin plate was used for inverse sizing. The final inverse problem was to estimate depth and width, whereas length was constrained based on the thickness of the panel. As well, the alignment of the signal in depth, z_0, was also included as an unknown in the inversion problem due to uncertainty about the precise start of the signal in the depth dimension (the top of the plate) for the Nortec data. Inversion results are presented in the Table 2. Sizing results were generally good with 2 of 3 cracks having < 10% error. Inversion using the 'edge models' appears to perform fairly well for the through crack cases (which was not demonstrated in [3]). However, the inversion results may be poorer compared to [3] because the inversion problem is more complex and must address the alignment of the signals, z_0, a new unknown. One case with a higher than expected error in the estimates and mean squared error (MSE) does appear to be off in alignment (z_0) by ~20 mils in the depth dimension (over a 0.100" thick plate). Errors in the model used for simulating fine crack widths may also be playing a role in the poorer inversion results. Further study and refinement of the inversion process is needed to ensure the inversion results are more consistent.

TABLE 2. Through crack sizing results using the VIC-3D® surrogate model with two edges for the Nortec BHEC data.

Sample #	depth_est (mils)	length_est (mils)	width_est (mils)	depth,best knowledge (mils)	length, best knowledge (mils)	width, best knowledge (mils)	MSE	z_0_est (mils)
203	19.31	100	2.78	18	100	0.1	0.0011	46.72
202	17.26	100	5.00	25	100	0.1	0.0028	62.395
201	31.15	100	4.56	31	100	0.1	0.0022	36.719

Inversion results in this section are presented for a series of cracks of increasing size ranging from mid-bore to through cracks. At the small end, the cracks start as mid-bore cracks. As they grow in length, the crack edges meet up with the sides of the 0.250" plate and a transition to through crack profiles occurs. The depths at the two sides of the plate for these through crack were measured and the average depth values are reported in Table 3 and used to verify the inversion results. Again, while a great deal of 'through crack' specimens were manufactured, few of the cracks are shallow in depth, below 50 mils deep. New inversion results using ABHEC data for select mid-bore and through cracks are presented in Table 3. For cases where there is a transition from through to mid-bore cracks, both surrogate models were considered. The mid-bore fit was found to be a better match with the two smaller cracks. Note, for the two mid-bore cracks, the estimated length results did hit the constraint on mid-bore length. In general, the sizing results are reasonable for the smallest three cracks. However, it appears to be difficult to estimate depths accurately beyond 50 mils using the 200 kHz BHEC inspection. One issue with the large crack data is signal saturation for one of the two channels. Note, that the values for z_0_est for the through and mid-bore cracks are inherently different. For the through cracks, z_0_est represents the start of the edge of the notch indication (ref. - 40 mils from entering the hole). For the mid-bore cracks, z_0_est represents the center of the response for the mid-bore crack (ref. - 40 mils from the start of signal). This -40 mil difference has to do with how the signal rises as the probe enters the bolt hole.

Distribution A. Approved for public release (PA): distribution unlimited.

TABLE 3. Select mid-bore and through crack sizing results using the VIC-3D® surrogate model with edges for the ABHEC data. Sample # 79 used for model calibration

Sample #	depth_est (mils)	length_est (mils)	width_est (mils)	depth_c.i. (mils)	fit type	depth,best knowledge (mils)	length, best knowledge (mils)	MSE	z_0_est (mil)
83	15.62	250**	0.12	2.46	mid-bore	10*	250	0.0023	171.1
74	17.88	250**	0.12	3.03	mid-bore	27	250	0.0029	174.2
79	48.03	250	0.31	5.51	through	50	250	0.0022	38.87
78	48.59	250	0.47	6.03	through	85	250	0.0023	31.04
77	54.19	250	0.89	10.34	through	124	250	0.0025	31.44

* estimated depth from crack growth models. **length estimates associated with constraint on mid-bore crack model.

Inversion results for the corner crack data sets are presented in Table 4. Getting good inversion results is shown here to depend on having the signals aligned well in the direction of the hole depth with the model. To address corner crack inversion, NLSE inversion introductory steps were implemented to (1) iteratively align the signals in the depth dimension and (2) to verify which direction the corner crack signal is oriented. These steps are critical to achieve the best model match for corner crack inversion estimating length, depth, and width simultaneously. The inversion approach did consider both corner and through crack fits, with corner crack fits demonstrating better MSE fit results. Concerning the inversion results, the depth estimates were satisfactory for the smallest two cracks. However, it was found to be difficult to estimate depths accurately for the largest cracks with the 200 kHz BHEC inspection, especially for saturated signals. Some error with the initial estimate of the corner crack orientation was observed. Knowledge of the layer thickness can greatly improve this evaluation.

TABLE 4. Select corner crack sizing results using the VIC-3D® surrogate model with edges for the ABHEC data. Sample # 79 used for model calibration

Sample #	depth_est (mils)	length_est (mils)	width_est (mils)	depth_c.i. (mils)	fit type	depth,best knowledge (mils)	length, best knowledge (mils)	MSE	crack dir.
49	36.682	155.36	0.43	2.7	corner	52	93	0.0019	-1
56	90.045	187.57	0.74	32.8	corner	105	192	0.0031	1
61	98.697	183.63	1.68	35.2	corner	153	268	0.0058	-1
79	53.198	250	2.11	10.2	through	50	250	0.0026	NA

CONCLUSIONS AND FUTURE WORK

This work presents a comprehensive approach for the model-based inversion of crack characteristics using eddy current nondestructive evaluation (NDE) demonstrated for a bolt-hole eddy-current (BHEC) technique. New model results were presented that better address the effect of having a corner crack at an edge and a through crack adjacent to two edges. A two-step inversion process was implemented that first evaluates the material layer thickness, crack type and location, in order to select the most appropriate VIC-3D® surrogate model for crack sizing. The final step in the inversion process is simultaneously evaluating crack depth, length and width (opening) for the eddy current signal. Inversion results for select mid-bore, through and corner crack specimens are presented where sizing performance was found to be satisfactory in general, but also depends on the size and location of the flaw. Lower frequency measurements are especially needed to improve the sizing of deep cracks.

In general, the UniWest ABHEC system data is ideal for supporting model-based inversion sizing of BHEC indications. However, two outstanding challenges exist in working with the system. First, when following standard procedures, there is often saturation in one of the two signals impacting inversion performance. Second, there is a distortion of the eddy current signals due to filtering, which produces a very different characteristic response in the circumferential direction. Recent work by Oneida et al., [8], shows promise for removing the effect of filtering prior to the application of model-based inverse methods. Further studies and refinement of the filter compensation process for the BHEC techniques are needed to ensure the inversion results are consistent and accurate.

Lastly, progress was also made on the development of an inverse method automated data analysis (INV-ADA) toolkit. An example view of the user interface is shown in Figure 7. The main objective of the toolkit is to provide

Distribution A. Approved for public release (PA): distribution unlimited.

software tools to enable NDE engineering and inspectors to perform EC inversion and subsequent data review. The interface provides the following features: select data set(s) for calibration and inversion, a means to calibrate the VIC-3D® model with calibration data from a known EDM notch, perform model-based inversion sizing of indication in BHEC data, and lastly, training features using VIC-3D® parametric surrogate models.

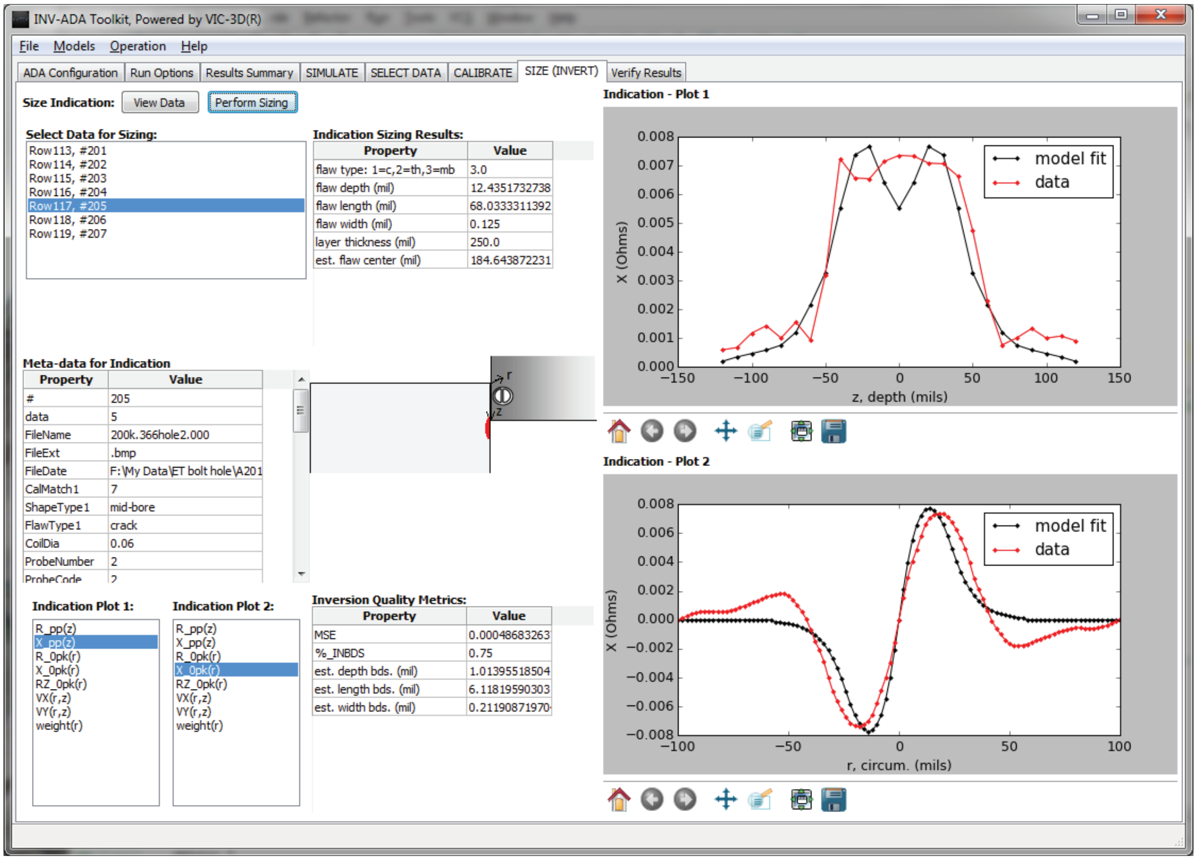


FIGURE 8. Prototype inverse method automated data analysis (INV-ADA) software interface

ACKNOWLEDGMENTS

The authors would like to acknowledge support for this work by the Air Force Research Lab (AFRL) under the SBIR Phase II Contract FA8650-12-M-5149 with Victor Technologies LLC.

REFERENCES

1. Lindgren, E. A., Knopp, J. S., Aldrin, J. C., Steffes, G. J., and Buynak, C. F. “Aging Aircraft NDE: Capabilities, Challenges, and Opportunities”, in *Review of Progress in Quantitative Nondestructive Evaluation*, eds. D. O. Thompson and D. E. Chimenti, (American Institute of Physics 894, Melville, NY) **26**, 1731-1738 (2007).
2. Sabbagh, H. A., Murphy, R. K., Sabbagh, E. H., Aldrin, J. C., and Knopp, J. S., *Computational Electromagnetics and Model-Based Inversion - A Modern Paradigm for Eddy-Current Nondestructive Evaluation*, Springer, (2013).
3. Aldrin, J. C., Sabbagh, H. A., Sabbagh, E. H., Murphy, R. K., Keiser,M., Forsyth,D. S., and Lindgren, E. A., “Model-based Inverse Methods for Bolt-hole Eddy Current (BHEC) Inspections,” *Review of Progress in QNDE*, Vol. 33, AIP, (2014).
4. Aldrin, J. C., Sabbagh, H. A., Annis, C., Shell, E. B., Knopp, J., and Lindgren, E. A., "Assessing Inversion Performance and Uncertainty in Eddy Current Crack Characterization Applications", in *Review of Progress in*

Distribution A. Approved for public release (PA): distribution unlimited.

Quantitative Nondestructive Evaluation, eds. D. E. Chimenti and L. J. Bond, (American Institute of Physics 1650, Melville, NY) **34**, 1873-1883 (2015).

5. Shell, E. B., Aldrin, J. C., Sabbagh, H. A., Sabbagh, E. H., Murphy, R. K., Mazdiyasni, S., and Lindgren, E. A., "Demonstration of Model-Based Inversion of Electromagnetic Signals for Crack Characterization," in *Review of Progress in Quantitative Nondestructive Evaluation*, eds. D. E. Chimenti and L. J. Bond, (American Institute of Physics 1650, Melville, NY) **34**, 484-493 (2015).
6. Motes, D., Aldrin, J. C., Keiser, M., Steffes, G., and Forsyth, D. S., "GMR sensing array technique validation study for the inspection of multi-layer metallic structures," in *Review of Progress in Quantitative Nondestructive Evaluation*, eds. D. O. Thompson and D. E. Chimenti, (American Institute of Physics 1511, Melville, NY) **32**, 1562-1569 (2013).
7. Murphy, R. K., Sabbagh, H. A., Sabbagh, E. H., Zhou, L., Bernacchi, W., Aldrin, J. C., Forsyth,D. S., and Lindgren, E. A., “Nondestructive damage characterization of complex aircraft structures by inverse methods: advances in multiscale models,” in *Review of Progress in Quantitative Nondestructive Evaluation*, Vol. 35, AIP, (to be published, 2016).
8. Oneida, E. K., Shell, E. B., Aldrin, J. C., Sabbagh, H. A., Sabbagh, E. H., Murphy, R. K., Mazdiyasni, S., and Lindgren, E. A., "Flaw Characterization using Inversion of Eddy Current Response and the Effect of Filters and Scan Resolution," in *Review of Progress in Quantitative Nondestructive Evaluation*, Vol. 35, AIP, (to be published, 2016).

Distribution A. Approved for public release (PA): distribution unlimited.